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A NEW WIDE PAIR OF COOL WHITE DWARFS IN THE SOLAR NEIGHBOURHOOD

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ABSTRACT

We report the discovery of a wide pair (93 arcsec angular separation) of extremely cool ($T_{eff} < 4000$ K) white dwarfs with a very large common proper motion (~ 1.9 arcsec/yr). The objects were discovered in a high proper motion survey in the poorly investigated southern sky region with $\delta < -60°$ using SuperCOSMOS Sky Survey (SSS) data. Both objects, SSSPM J2231-7514 and SSSPM J2231-7515, show featureless optical spectra. Fits of black-body models to the spectra yield effective temperatures of 3810 K and 3600 K, respectively for the bright ($V = 16.60$) and faint ($V = 16.87$) component. Both degenerates are much brighter than other recent discoveries of cool white dwarfs with comparable effective temperatures and/or $B_J - R$ colours. Therefore, they should be relatively nearby objects. The comparison with other cool white dwarfs and a photometric distance determination yield distance estimates between 9 pc and 14 pc. The latter seems to be more realistic, since the good agreement of the proper motion of both components within the errors of about 8 mas/yr and the angular separation between the two stars support a distance of about 15 pc with relatively small masses of the components. With smaller distance we should be able to measure a differential proper motion due to orbital motion if the orbital plane is not strongly inclined and the present orbital velocity vector is not close to the line of sight. The space velocity based on that distance and assumptions on radial velocity makes the new pair of extremely cool white dwarfs some of the probably oldest members of the Galactic disk population, although the possibility that these objects are part of a Galactic halo dark matter component can also not yet be ruled out.

Subject headings: astrometry — binaries: general — dark matter — Galaxy: halo — solar neighbourhood — white dwarfs

1. INTRODUCTION

Cool white dwarfs are interesting objects for a number of reasons such as determining the age of the Galactic disk (Leggett, Ruiz and Bergeron 1998) and as possible components of the Galactic dark matter halo (Ibata et al. 2000; Oppenheimer et al. 2001b). A detailed photometric and spectroscopic analysis of all known cool white dwarfs (4000 K< T_{eff} < 12000 K) with trigonometric parallax measurements was summarised by Bergeron, Leggett and Ruiz (2001). Additionly there are a number of recent discoveries of cool white dwarfs with effective temperatures below 4000 K (Hambly, Smartt and Hodgkin 1997; Ibata et al. 2000; Harris et al. 2001; Oppenheimer et al. 2001b), one of which, WD 0346+246, has a trigonometric parallax measurement (Hambly et al. 1999).

As shown by Oppenheimer et al. (2001b), the temperature of cool white dwarfs is well correlated with the $B_J - R$ colour of photographic plates taken with the United Kingdom Schmidt Telescope (UKST). Oppenheimer et al. (2001b) have also presented a photographic colour-colour diagram ($B_J - R$) vs. ($R - I$) of cool white dwarfs together with curves of synthetic colours expected for different chemical compositions. These observations can now be used for confirmation of recent theoretical models on the formation of molecular hydrogen in cool white dwarf atmospheres leading to collisionally- induced opacity at wavelengths longer than 6000Å (Hansen 1998).

2. DISCOVERY OF THE COMMON HIGH PROPER MOTION PAIR

Several high proper motion surveys have been carried out recently with the aim of completing the proper motion catalogues of Luyten, e.g. Luyten (1979), at fainter magnitudes and finding new low-luminosity objects (Monet et al. 2000; Scholz et al. 2000; Ruiz et al. 2001; Oppenheimer et al. 2001b). Most of these efforts are concentrated on the southern sky with $\delta < -33°$, where the main source for Luyten's catalogues is the Bruce Proper Motion Survey, most of whose plates reach only to about $m_{pg} = 15.5$. In the northern sky, Luyten's catalogues are based on observations with the Palomar Schmidt telescope.

Recently, the entire southern sky has been scanned in two passbands (B_J and R), with additional scans of plates at different epochs and in other passbands (including I) over large sky areas (Hambly et al. 2001a,b,c) - (hereafter SSS). SSS data were the observational basis of the recent survey for cool white dwarfs by Oppenheimer et al. (2001b), covering about 10% of the sky around the South Galactic Cap. We have made use of the same observational material but our search was carried out in a region close to the south celestial pole, at declinations $\delta < -60°$, where in

most fields three different epoch measurements on UKST B_J and R plates and ESO R plates were available.

The basic reduction consisted of a re-matching of previously (i.e. within a standard identification radius of 3 arcsec) unmatched objects and the subsequent determination of proper motions using linear regression over the SSS measured coordinates at three epochs. The search area is difficult to estimate as well as the completeness of the survey. This is due to the fact that in many fields the epochs of two of the plates were very close to each other. On the other hand we made a rather restrictive preselection of undisturbed star-like objects based on their image parameters, in order to exclude spurious matching leading to false proper motions. Therefore, we do not attempt to draw conclusions on the statistical properties of the survey, but just present the discovery of the two objects with the largest proper motion obtained so far in the SSS data.

The coordinates, photographic photometry and the proper motions of the two high proper motion stars are given in Table 1. The I band magnitudes (as well as the corresponding extra-epoch positions used in the proper motion solution) were kindly provided to us by Nigel Hambly. A further improvement of the proper motion solution was achieved from including additional positions measured on the recent epoch acquisition images. These positions were obtained in the system of the SSS catalogues by using all stars with small proper motions in a field of 15×15 arcmin^2 as reference stars (see note to Table 1). There is no significant difference between the proper motions of the two components. Since the discovery of the wide pair of cool white dwarfs with very large common proper motion is based on SSS data, we have given them the names SSSPM J2231-7514 and SSSPM J2231-7515.

SSSPM J2231-7515 (but not its companion since it was brighter than the survey limit) was also discovered in another on-going program using APM measures of the same UKST sky survey plates (Ibata et al. 2000), which also aims to find cool high proper motion white dwarfs.

3. OBSERVATIONS

3.1. *DFOSC observations*

Observations of the new common proper motion pair were carried out using the *Danish Faint Object Spectrograph* (*DFOSC*) on the Danish 1.54m Telescope in La Silla. Data were taken during the nights starting June 19-20, 2001 (local time) in relatively good almost photometric conditions.

Seeing varied slightly during these nights between 1.0 and 1.2 arcsec. Only short V-band (Bessel) images were taken that are relevant to our objects as acquisition images (Figure 1). Spectroscopy was done using a 2.0 arcsec wide long-slit (corresponding to 5.1 pixels in imaging mode), positioning both objects on the slit at the same time. Two grisms were used, number-5 (5200-10200Å, 7000Å blaze, 3.3Å/pixel resolution – one 1800s spectroscopic observation) and number-7 (3800-6800Å, 5250Å blaze, 1.65Å/pixel resolution – a 1800s and a 1300s spectroscopic observation). Two spectrophotometric standards were taken using each grism, LTT 7379 and LTT 9239 (Hamuy et al. 1992, 1994), as well as a large number of zero, flat (both for imaging and spectroscopy for all grisms used) and arc-lamp (for both grisms) calibration frames. For broad-band photometric calibrations, Landolt standard fields (Landolt 1992) were observed repeatedly.

3.2. *EFOSC observations*

After completing the reduction of the DFOSC observations, we realised that a spectrum of one of the objects, SSSPM J2231-7515, which was discovered independently, had already been observed half a year earlier. The spectrum of this star was observed with the EFOSC spectrograph on the ESO 3.6m telescope during the night of 2 December 2000. A slit width of 1.5 arcsec was used with grism number 1 (3185-10940Å, 4500Å blaze, 6.30Å/pixel resolution) for three exposures of 300s each.

4. DATA REDUCTION

All of the data was reduced in the standard manner using IRAF procedures. Consequently in the following sections we only describe important results or deviations from normal.

4.1. *DFOSC data*

For the imaging data all images were bias-corrected, trimmed and then flat-fielded using twilight flats. After measuring photometric zeropoints in 6 standard fields (Landolt 1992), we adopted a zeropoint of 24.66 (for 1s exposure time and airmass of 1.45 – the airmass of our acquisition frames) in the Bessel V-band. Examination of the measured zeropoints shows that conditions were very close to photometric (with a hint of very weak cirrus in some cases). Using this zeropoint, we measured the (Vega) magnitudes of the two objects to be 16.60 and 16.87 in V (Bessel). We also measured the magnitude of the extra object, accidentally landing on our 2 arcsec wide slit (see below) to be 16.86 (see Figure 1). Instrumental magnitude errors are small (1-2%), the main source of error is the determination of the zeropoint. We therefore estimate the overall accuracy of these magnitudes to be better than 5%.

Spectroscopic frames (science and standard fields and calibration frames) were also bias and zero subtracted, trimmed and flatfielded (using different flat-field frames for the two grisms). The only complication was the removal of focal plane geometric distortions to improve the sky subtraction. This was done by tracing lines in the wavelength calibration frames. A smooth distortion map was fitted to the results and was applied to all frames.

All objects on the slit were traced along the dispersion axis. Sky subtraction was done through fitting in a 35 arcsec wide band, centered on the object, excluding the central 16 arcsec region. A relatively wide aperture was defined for all objects, which includes all the flux (but degrades the S/N slightly). Object spectra were 'optimally' extracted within this aperture, with both cosmic-ray removal (based on photon statistics) and a weighted sum based on estimated signal-to-noise ratio.

Wavelength calibration was done using He-Ne arc exposures. For the number-7 grism (bluer, higher resolution) the procedure worked quite well (0.06Å RMS, 0.15Å maximum deviation) in the wavelength range 3889-6717Å. For the number 5 grism (red, lower resolution), the accuracy is worse (as expected), around 0.5Å RMS (peak deviation

is 1Å), in the range of 5852-8783Å. In addition, the exact position of the object on the slit can also introduce an additional, systematic shift of the spectra. This later effect is estimated to be 1.5Å for the lower resolution and 0.8Å for the higher resolution grism. These estimates were also verified by checking emission lines in the sky background.

It is important to note that beyond 7000Å the CCD suffers from serious fringing, which we could not remove.

Flux calibration was attempted by observing two standard stars in the same two grism configurations. However, during the reduction we encountered several problems with the red end calibration possibly related to the fringing. The serendipitously observed 3rd object in the slit turned out to be a K0-K1 star. Using a library spectrum (Jacoby et al. 1984), we corrected the continuum slope of this object and used this smooth correction to reduce the calibration problems for the two white dwarfs. The quality of this correction was checked by comparing overlapping regions in wavelength in different observations. For the K-star, differences were less than 1%. For the fainter high proper motion object (which is closer to the K-star), differences were 1-2%, showing no colour dependence. For the brighter high proper motion object, differences were 5%. These residual differences were assumed to be 'grey' effects (i.e. not depending on wavelength).

Finally we calculated synthetic Bessel-V magnitudes for the objects from the spectra. In the case of the brighter object, the measured broad-band magnitude was reproduced better than 1%, while for the fainter one a 9% difference was measured. We applied a (colour independent) correction to match the spectrum to the measured broadband magnitudes.

The resulting spectra are shown in Figure 2. Assuming that our correction was right, fluxes are accurate to 5-10%, but in any case, not worse than 40% (which *can* be a colour dependent effect). As all our corrections were smooth and the examination of the extracted raw spectra showed that this not well understood effect is also smooth, we are quite certain that we neither introduced nor removed fine structure (e.g. emission or absorption lines) in the data.

Both spectra were fitted with a black-body spectrum in the range 4300-6800Å (where our data are the most accurate). The fit values are 3810 K for the bright one and 3600 K for the faint one. If our reduction truly reproduced the correct continuum shape, the accuracy of these numbers is ±100 K. As we are not sure that we did not introduce a tilt in the spectra, we can only say with high degree of confidence that the temperatures are in the range of 3000-5000 K (clearly cool white dwarfs).

4.2. *Reduction of EFOSC data*

The three consecutive 300s exposures were combined to reject cosmic ray defects, and reduced in a way similar to that detailed above. The wavelength-calibration (by comparison to He-Ar lines) is accurate to 2.3Årms, and flux-calibration was performed by comparison to the standard star LTT2415. Contrary to the DFOSC observations however, the EFOSC spectrograph did not give rise to unexpected variations between exposures in the red part of the spectrum. The resulting spectrum of SSSPM J2231-7515 is shown in Figure 3.

We have fit two black-body curves to the spectrum of Figure 3. The solid line shows a fit to the red side ($\lambda > 6000$Å), which has a temperature of $T = 3800$ K, but which fails to follow the blue side of the spectrum. Fitting instead the blue end ($\lambda < 6000$Å), gives a cooler temperature of $T = 3100$ K (dashed line), but which gives a poor fit in the red. The study of cool white dwarf atmospheres by Bergeron, Ruiz and Leggett (1997) employed H- and He atmospheres to fit $BRIJHK$ colors and H-alpha lines. They also often found that the observed B-band flux was too faint for the best fit to $RIJHK$. This would suggest that an additional source of opacity exists near the B-band, and that the higher temperature value ($T = 3800$ K) is a better estimate for the true atmospheric temperature.

There is a good agreement of the latter temperature value with that obtained from the black-body fit to the DFOSC spectrum of SSSPM J2231-7515 (Figure 2). This confirms the corrections applied in the flux calibration of the DFOSC data and suggests both white dwarfs have equivalent black body temperatures <4000 K.

5. DISTANCE ESTIMATES

5.1. *Distance estimate based on magnitude and colour*

With the above temperatures, respectively of 3810 K and 3600 K (3100 K to 3800 K), the newly discovered objects are comparable to the coolest known white dwarf WD0346+246 with 3750 K (Hodgkin et al. 2000; Oppenheimer et al. 2001a) for which a trigonometric parallax of 36±5 mas (28±4 pc) has been measured (Hambly et al. 1999). If we assume our objects to have the same physical properties (temperature, mass, chemical composition) as WD0346+246, we can estimate their distance from a comparison of their apparent V magnitudes. With $V = 19.06$ (Oppenheimer et al. 2001a), WD0346+246 is more than two magnitudes fainter than our objects (16.60 and 16.87), and consequently we get distance estimates of 9 pc and 10.2 pc. These distance estimates have the same relative uncertainty as for the comparison object, i.e. ±1.3 pc and ±1.5 pc, respectively, and rely on the assumption of identical physical properties, which is unlikely to be the case.

For an alternative distance estimate we can apply the photometric parallax relation given in Oppenheimer et al. (2001b):

$$M_{B_J} = 12.73 + 2.58(B_J - R). \qquad (1)$$

With the B_J magnitudes and $B_J - R$ colours from Table 1 we get 14.1 pc and 13.1 pc, respectively for the bright and faint component of our cool white dwarf pair with an uncertainty of about 20%. All objects listed in Table 1 of Oppenheimer et al. (2001b), with comparable colour ($B_J - R > 1.5$) to our newly discovered objects, are at least two magnitudes fainter in B_J. The fainter component, SSSPM J2231-7515 is with $B_J - R = +1.75$ and $R - I = +0.63$ very close to the colours of the two known extremely cool white dwarfs F351-50 and WD0346+246 as shown in the colour-colour-diagram of Oppenheimer et al. (2001b).

5.2. *Distance estimate based on kinematics and separation*

From the angular separation we can make an estimate of the expected differential proper motion due to orbital motion of the wide binary if we make plausible assumptions

for the total mass of the system and the orbital characteristics. In Table 2 we give an example of the results for masses of both components respectively of 0.4, 0.6 and 0.8 solar masses in an assumed circular orbit perpendicular to the line of sight.

A conservative estimate of the proper motion errors based on the formal errors and on the change in proper motion with different numbers of distinct epoch positions included in the solution (see Table 1), gives 8 mas/yr. Since we measure zero differential proper motion within these errors, we can conclude that for a circular orbit as above the distance must be at least about 15 pc even allowing for some inclination of the orbit. Only in the case of an almost edge-on orbital plane with respect to the line of sight and both components located such that their orbital motion manifests itself mainly in line-of-sight radial velocity, would we see no differential proper motion for smaller ditances.

We have also computed possible heliocentric space velocities based on assumptions on distance and radial velocity of the cool white dwarf pair. The distance estimates of about 10 pc to 15 pc, based on magnitude and colour and on the angular separation and the not measurable differential proper motion, already lead to rather large space velocities. However, clear halo-like space velocities are only computed assuming 25 pc to 30 pc distance, which is probably not realistic given the magnitudes and temperature estimates.

6. CONCLUSIONS

A common proper motion pair with the very large proper motion of about 1.9 arcsec has been discovered from SuperCOSMOS Sky Survey data. Both objects, SSSPM J2231-7514 and SSSPM J2231-7515, were classified from follow-up spectroscopy as featureless cool white dwarfs. Effective temperatures of both objects were obtained by fitting the flux-calibrated spectra with black-body models. If the temperature estimates are correct, the newly discovered white dwarfs belong to the small number of presently known extremely cool white dwarfs with $T_{eff} < 4000$ K. With a distance of about 10 pc to 15 pc, obtained from comparison with other known cool white dwarfs, they would also be the nearest objects of that temperature class. A conservative temperature estimate of $T_{eff} < 5000$ K still makes the new objects interesting for follow-up observations, since they would be only the second known double degenerates in that temperature class within about 25 pc (after LHS 239 and LHS 240). Currently, there are only 11 cool white dwarfs with $T_{eff} < 5000$ K and trigonometric parallaxes of less than 25 pc (Bergeron, Leggett and Ruiz 2001). All presently known or suspected degenerates with $T_{eff} < 4000$ K are at trigonometric or photometric distances of more than 25 pc (Hambly et al. 1999; Ibata et al. 2000; Harris et al. 2001; Oppenheimer et al. 2001b).

Further investigation of the new objects is obviously needed. A trigonometric parallax measurement and further improvement of the (differential) proper motion analysis of the wide binary will allow a mass estimate. The trigonometric parallax will also be important for the classification of the new pair of cool white dwarfs as Galactic disk or halo components. From the current estimates, based on the available data and some assumptions, the objects might be among the coolest and oldest Galactic disk white dwarfs, although we can not yet exclude the possibility that they belong to the dark matter component of the Galactic halo. Accurate photometry, including IR photometry is needed to constrain the amount of absorption due to molecular hydrogen. Our first attempts to estimate the temperature by black-body fits provided only preliminary values. As shown by Oppenheimer et al. (2001a), the physical parameters of cool white dwarfs can only be obtained from fitting synthetic spectra to the observed spectral energy distribution. Since the objects are rather bright, higher resolution spectroscopy can be carried out and one can attempt to measure their radial velocity if any lines can be resolved.

This research has made use of the SuperCOSMOS Sky Surveys, i.e. digitized data obtained from scans of UKST and ESO Schmidt plates. We would like to thank the SuperCOSMOS team for producing such excellent data. We thank Nigel Hambly for helpful discussion and for providing us with the I band SSS data.

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Table 1
SSS positions, photographic photometry and proper motions

Object SSSPM...	RA and DEC J2000, epoch 1996.775	B_J UKST	V CCD	R ESO	R UKST	I UKST	$\mu_\alpha \cos\delta$ mas/yr	μ_δ mas/yr
J2231-7514	22 30 39.613 -75 13 49.36	17.27	16.60	15.77	15.82	15.25	$+404 \pm 7$	-1824 ± 9
J2231-7515	22 30 33.141 -75 15 18.43	17.83	16.87	16.08	16.08	15.45	$+404 \pm 5$	-1829 ± 8

Note. — V magnitudes were obtained from the acquisition images. The proper motions given in the table were determined from the SSS positions at four different epochs: 1977.782 (B_J), 1984.782 (R (ESO)), 1993.733 (I) and 1996.775 (R (UKST)). If we use the recent positions of our acquisition images (J2000, epoch 2001.470), 22 30 40.136 -75 13 58.08 (SSSPM J2231-7514) and 22 30 33.688 -75 15 27.10 (SSSPM J2231-7515) in addition to the SSS positions, we obtain a proper motion of $+408 \pm 5, -1828 \pm 7$ mas/yr and $+409 \pm 5, -1831 \pm 5$ mas/yr, respectively.

Table 2
Expected differential proper motion due to orbital motion

distance	separation	$2 \times 0.4M_\odot$		$2 \times 0.6M_\odot$		$2 \times 0.8M_\odot$	
		Orbital period	μ_{orb}	Orbital period	μ_{orb}	Orbital period	μ_{orb}
pc	AU	yr	arcsec/yr	yr	arcsec/yr	yr	arcsec/yr
5[a]	465	11000	0.052	9000	0.064	8000	0.074
10[a]	930	32000	0.018	26000	0.023	22000	0.026
15[a]	1395	58000	0.010	48000	0.012	41000	0.014
20[a]	1860	90000	0.007	73000	0.008	63000	0.009
25[a]	2325	125000	0.005	102000	0.006	89000	0.007
30[a]	2790	165000	0.004	135000	0.004	117000	0.005
10[b]	5270	428000	0.008	349000	0.009	302000	0.011
10[c]	930	32000	0.003	26000	0.004	22000	0.005
10[d]	930	15000	0.012	12000	0.016	10000	0.018

[a]Computations for the first six rows are based on the measured angular separation of 93 arcsec, the assumed equal masses for both components and a circular orbit in the plane perpendicular to the line of sight. For the results shown in the last three rows, additional assumptions were made.

[b]80° inclination of the orbit in North-South direction

[c]80° inclination of the orbit in East-West direction

[d]No inclination, but eccentricity of 0.6 with stars at apastron.

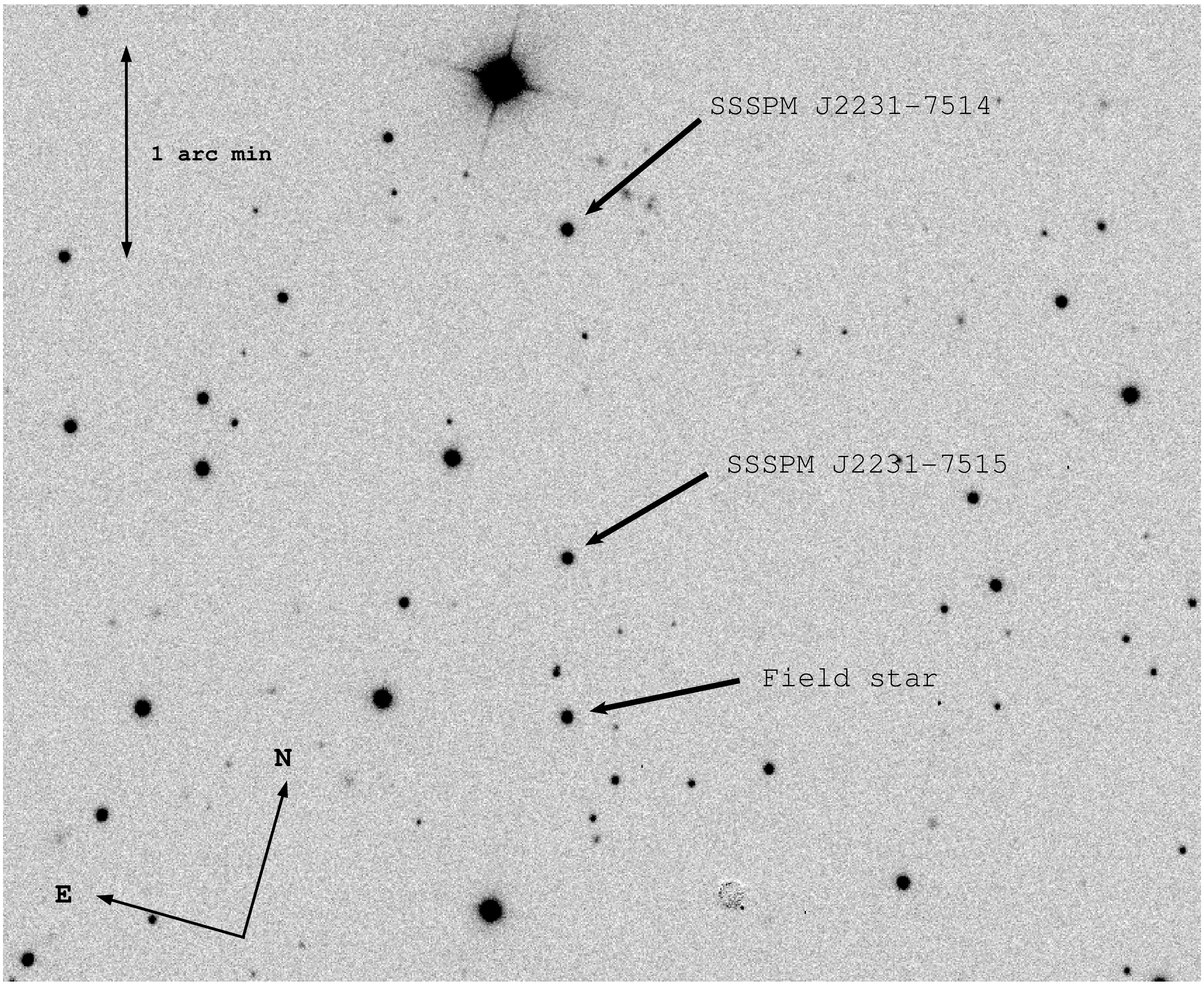


Fig. 1.— The V band acquisition image taken at epoch 2001.47, where the components of the high proper motion pair are marked together with a field K-star which was exactly on the slit and could be used for an additional check of the flux calibration of the spectra.

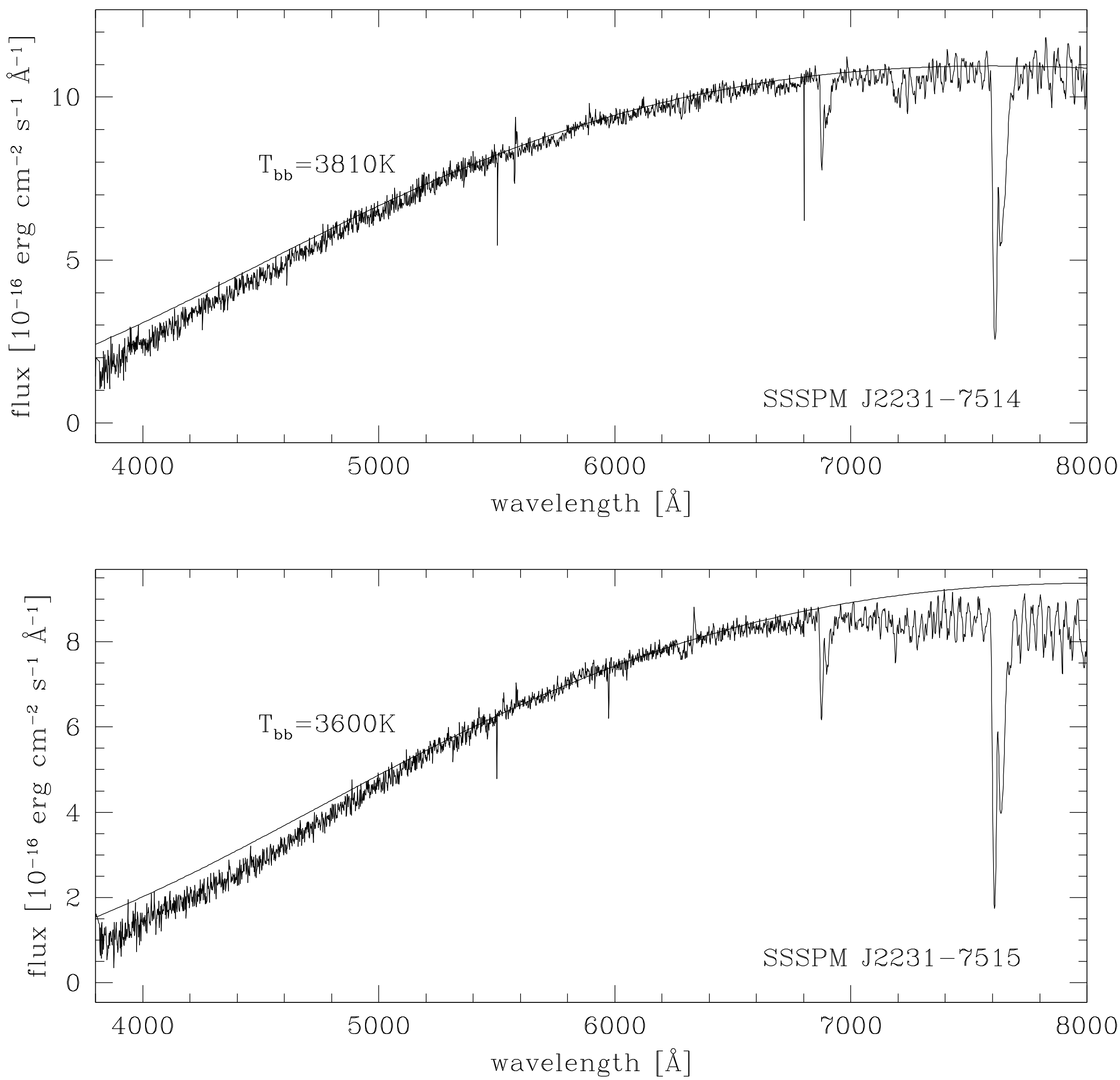
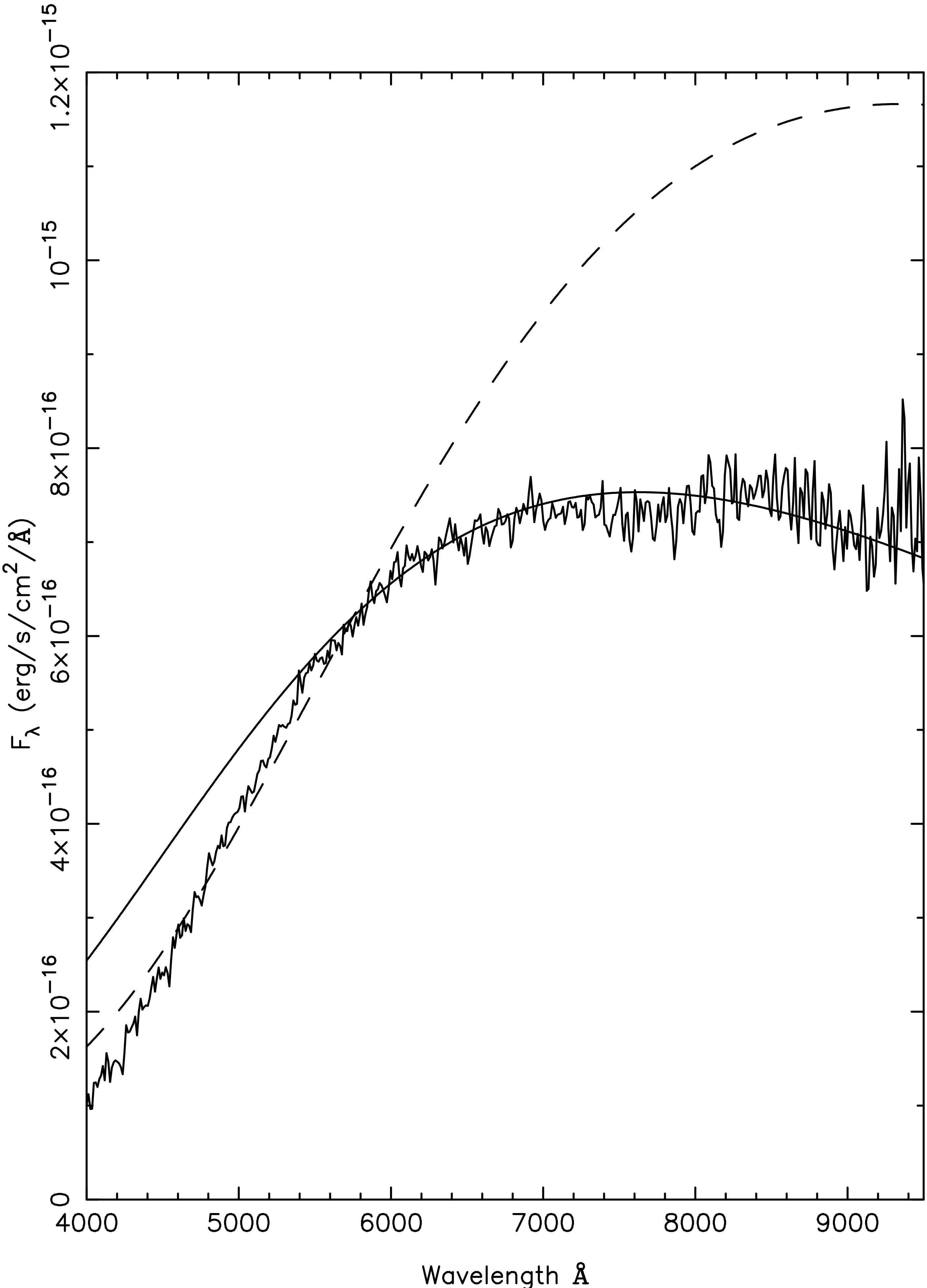


Fig. 2.— Flux calibrated spectra obtained with the Danish 1.5m telescope using DFOSC. The atmospheric A- and B-band, which we did not remove, are the only features seen in the spectra. The red part of the spectra (> 7000Å) suffers from fringing. There are no spectral features which could be associated with the objects. We classified both of them as extremely cool white dwarfs. Black-body fits to the spectra in the range 4300-6800Å (shown by overlaid solid lines) yielded temperatures of 3810 K and 3600 K, respectively for the bright and faint component.



1.2×10^{-15}
10^{-15}
8×10^{-16}
6×10^{-16}
4×10^{-16}
2×10^{-16}
0
F_λ (erg/s/cm^2/Å)
4000
5000
6000
7000
8000
9000
Wavelength Å